NASA/TP-2014-218557

Development of Procedures for Manufacturing E-Textiles with Machine Embroidery

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October 2014

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1.0 Introduction

Wearable Electronic-textile Application & Research (WEAR) Lab's primary focus is on developing electronic-textiles (e-textiles) and wearable technologies. An e-textile combines traditional textiles, such as fabric and thread, with electronics elements, such as microcontrollers, sensors, light-emitting diodes (LEDs), displays, and tactors. Previously, the WEAR lab developed e-textiles by either sewing or embroidering conductive interconnects using conductive silver thread. Next, components would be either hand sewn or soldered in place. However, there have been difficulties in working with conductive threads as they are prone to fraying, breaking, and curling, especially when used in an embroidery machine. Further, hand sewing components in place is tedious and has led to component connections that would break down over time from strain.

The WEAR lab recently acquired a Brother PR-650e embroidery machine, which allows for both larger e-textiles to be manufactured, as well as for greater control over thread tension. In developing procedures for using the Brother PR-650e to manufacture e-textiles, work was broken into individual phases. As lessons were learned from each phase, recommendations were made on what to adjust for the next phase.

Figure 1: PR-650e embroidery machine.

2.0 Phase One – Embroidering with Conductive Thread

2.1 Overview and findings

For my first embroidered e-textile project, I designed a circuit that will light up three LEDs while a button is pushed. After designing the circuit and choosing components, I created a digital layout of how I wanted the components and circuits physically arranged. Lastly, I drew an embroidery design from this and sewed it on the embroidery machine. I chose Shld2NyAg-B conductive thread as it had previously performed better in embroidery over alternative threads. Shld2NyAg-B is 2-ply silver and nylon thread that is manufactured by Shieldex. Before placing components, I made four test runs—one with only conductive bobbin thread and straight-stitches, one with only conductive bobbin thread and satin stitches, one with conductive top and bobbin thread with straight stitches, and one with conductive top and bobbin thread with satin stitches. My findings were that the PR-650e has no issues with conductive bobbin thread; however, there are some very minor issues using this thread as the top thread. I also found that using satin stitches with conductive top and bobbin thread gave the lowest resistance. Components were not placed on either of the prototypes because some ‘tails’ at attachment points were found to be too short. I recommend either increasing the tails at the attachment points or finding another attachment method, and increasing the length of the satin stitches so that the components will have conductive ‘pads’ on which to rest.

2.2 Circuit design

The circuit was designed using mostly off-the-shelf components from Lilypad, including 3 small LED boards, a small switch board, and a small Lithium-ion battery connection board. The circuit also utilizes three standard 75-ohm resistors. The switch and battery are combined in series, with the three LEDs/resistors in parallel—green, blue, then green. I sketched a circuit diagram on paper, and then physically arranged the components using wires with clips to test the design.

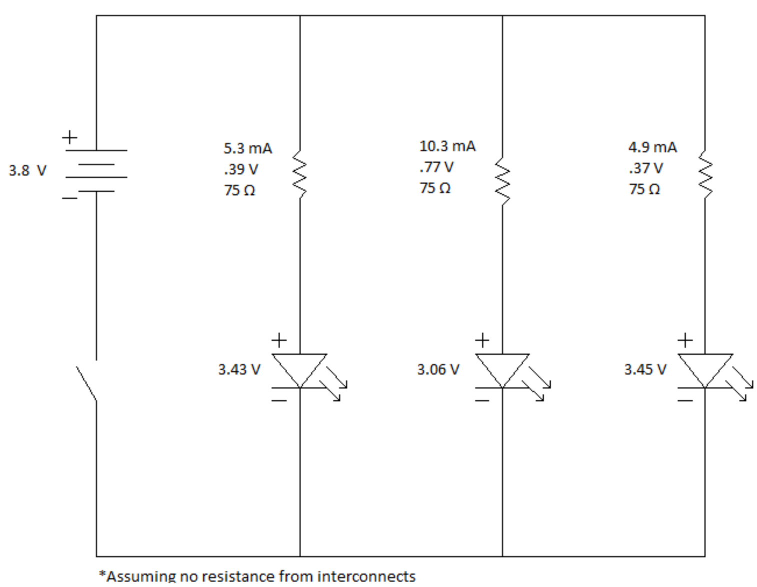

Figure 2: Circuit diagram.

2.3 Circuit arrangement

To physically arrange the components, I measured each component's size so that I would know how long to make the connections. Next, I created a draft on notebook paper of approximately how I wanted the circuit to be laid out. On the computer, I used AutoCAD to draw both the components and the connection stitches in 1:1 scale. This allowed me to precisely pinpoint where each component would rest in the embroidery hoop, and how long each connection had to be. For this project, I chose the 100 mm x 100 mm hoop, as it was large enough to hold all the components and small enough to use very few materials. After drawing the diagram of the circuit layout, I exported an image in the .jpg format, at 254 dots per inch (dpi)—each pixel representing 0.1 mm.

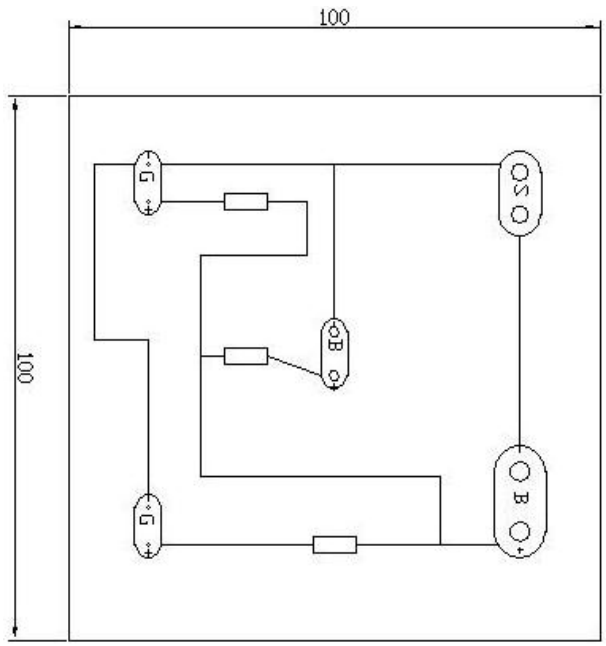

Figure 3: Circuit layout drawn in AutoCAD.

2.4 Embroidery design

To draw the embroidery design, I imported the circuit layout into PE-Design, which is Brother's embroidery digitizing software. PE-Design didn't automatically detect the dpi of the image—which I suspect is caused by AutoCAD's .jpg exporting algorithm. As such, the image was imported significantly smaller than required. Because PE-Design can be calibrated to allow one's monitor to display items at 1:1 scale, I was able to resize the image such that the hoop outline matched 10 cm on a ruler. Next, I had to move the background image into PE-Design's embroidery field—with the 100 mm x 100 mm hoop selected..

I made two versions of the design—the first using only straight stitches for connections, and the second using straight stitches encapsulated in satin stitches for connections. Straight stitches are faster, thinner, and simpler to sew. Encapsulating straight stitches in high-density satin stitches gives a bigger contact area between threads to reduce the impact of breaks and makes connections more durable. Connections were sewn up to the component attachment points. To create tails to which the components can attach, I drew short straight stitches near the top of the design. This way, when the machine finishes sewing a line, it will move the hoop a long distance, with unsewn thread being fed through. These jumps are shown as dotted lines. For the satin stitch design, I simply copied the straight stitches and converted them to ‘zigzag’ stitches. I made the satin stitches use a different color to allow for a machine stop after the straight stitches are sewn.

Notes: Background image must be saved in the same directory as the .pes file saved by PE-Design. Otherwise, the background image will not load the next time the .pes file is loaded.

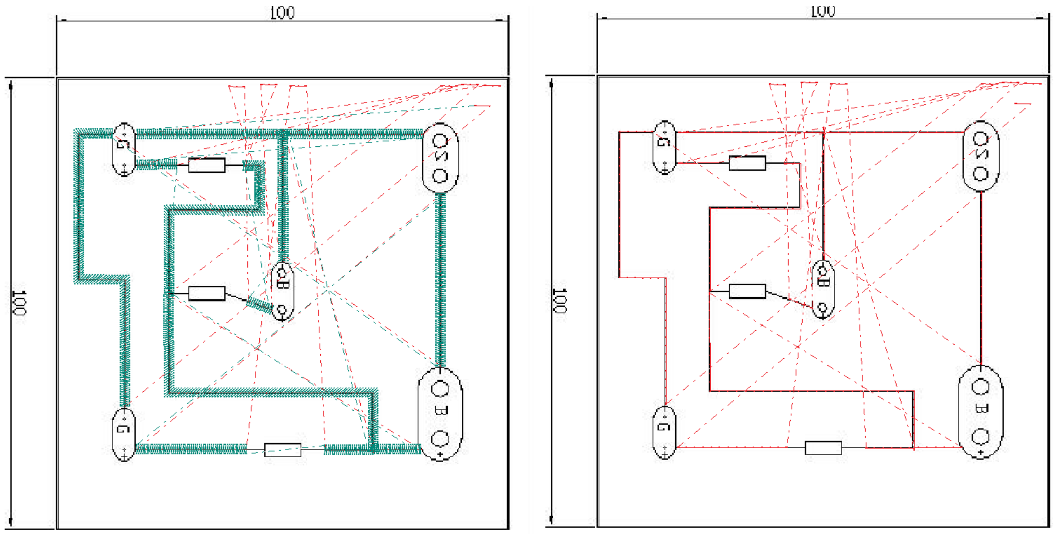

Figure 4: Digitized embroidery designs. Left: With satin stitches. Right: With straight stitches.

2.5 Sewing

I sewed two versions of both designs—one with conductive bobbin thread, and one with conductive bobbin and top thread. Each version was sewn onto two layers of stabilizer for added stability.

The machine was first loaded with Shld2NyAg-B silver conductive bobbin thread and regular colored embroidery thread on the top. Shld2NyAg-B was chosen as it had previously performed better in embroidery over alternative threads. First I sewed the conductive bobbin thread only circuits; both sewed without any mishaps. For the satin stitch design, I stopped the machine after the straight stitches were sewn, then removed the hoop to trim away unnecessary thread and to move the thread tails to a location where they would not be sewn over by the satin stitches. I used clear tape to hold the tails in place.

Next, I changed the machine needle settings to use conductive thread on top to sew the last two circuits. When putting the conductive thread on the spool, I also added a thread net and lowered the needle’s tension—I found that the tension was still too strong, which I suspect may have been from a combination of the thread net and the thread’s physical properties. As such, I lowered the tension even further. While sewing, I found that using conductive thread on the top is less effective than using conductive thread on the bottom. The thread was more prone to fraying, and also had more resistance to passing through the machine, which increased the tension; a common issue was that the thread would break when the machine did a jump over a long distance.

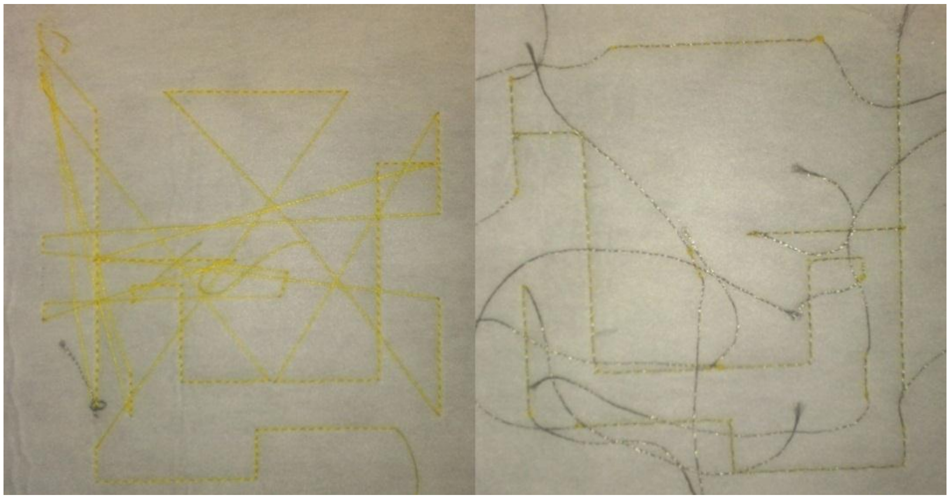

Figure 5: Conductive bobbin thread only with straight stitches, front and back.

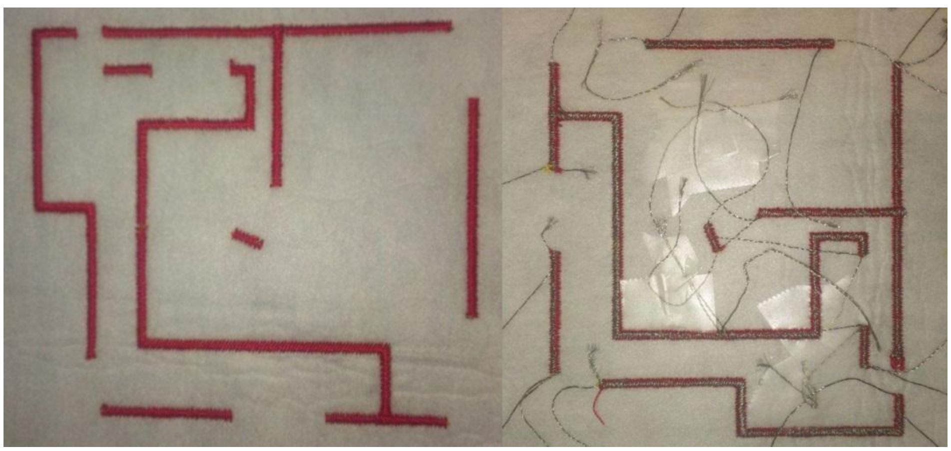

Figure 6: Conductive bobbin thread only with satin stitches, front and back.

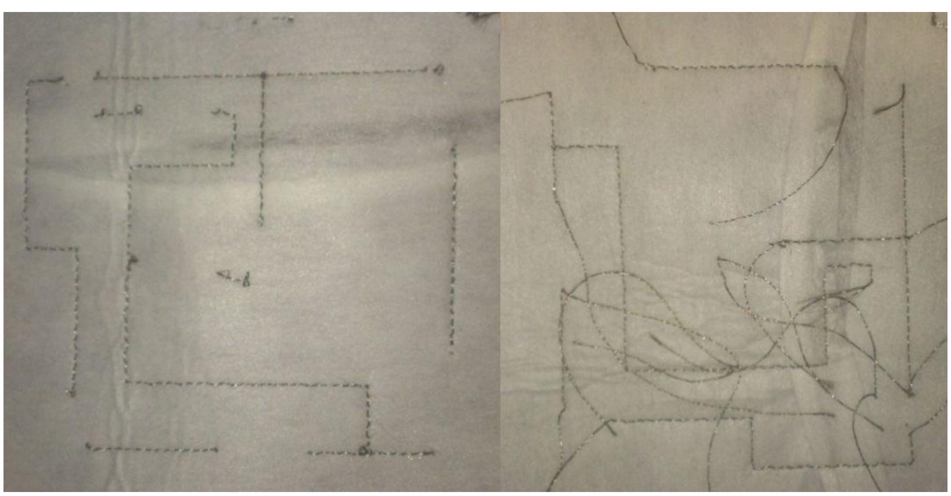

Figure 7: Conductive bobbin and top thread with straight stitches, front and back.

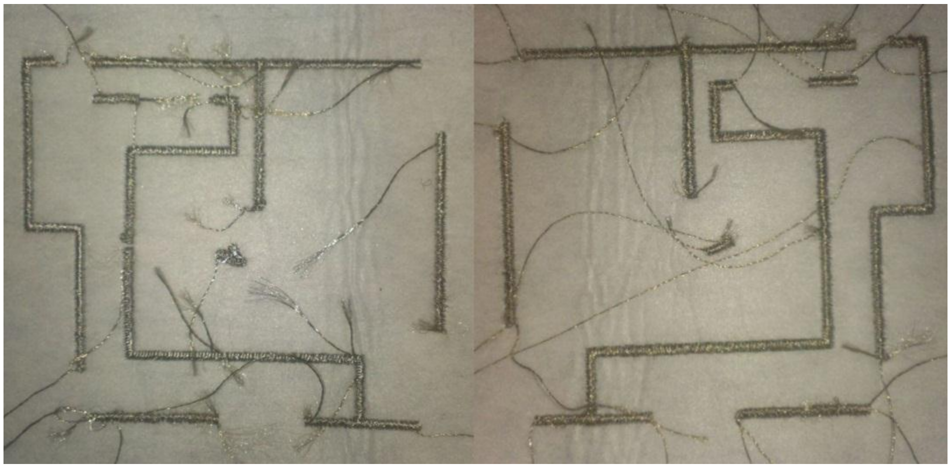

Figure 8: Conductive bobbin and top thread with satin stitches, front and back.

2.6 Results and Recommendations

I found that the two straight-stitch circuits—with conductive bobbin/nonconductive top thread and conductive bobbin/top thread—all had very similar resistance values around 4 ohms/inch. There was no clear advantage of using one method over the other. The circuit with conductive bobbin thread and satin stitches gave a small advantage at between 3 and 3.5 ohms/inch. I found that using conductive bobbin/top thread with satin stitches gave the best results with between 1.5 and 2 ohms/inch. Further, satin stitches allow a larger contact area when attaching components. I also found that in some areas, the ‘tails’ were shorter than needed for attaching components. Because of this, I decided not to attach components to the prototypes.

My recommendation for the next prototype is to either add longer tails or find a new attachment method, and to ensure a more reliable connection by increasing the length of the satin stitches so that the components will have conductive ‘pads’ to rest on.

3.0 Phase Two – Embroidering Circuits with Hand-Sewn Components

3.1 Overview and findings

Continuing from my first attempt, I created an e-textile circuit that lights up three LEDs while a button is pushed. For this attempt, I chose to use the pattern with satin stitches; I modified the design to include no tails and to have the satin stitches rest underneath the solder holes of the components. I chose Shld2NyAg-B as the top conductive thread and Sysc20VtAg as the bobbin conductive thread. Sysc20VtAg is a 20-filament silver-coated Vectran thread made by Syscom. It is advantageous because it has much-lower resistance. The PR-650e had no serious issues with sewing Sysc20VtAg as bobbin thread. Sewing with this combination gave a big improvement in resistance over the first attempt. Rather than attach components through sewing 'tails', I simply hand-sewed Sysc20VtAg between the solder points and the satin stitches. Overall, this method was very successful; however, hand-sewn connections were found to be unreliable as components eventually came lose.

3.2 Embroidery design

I optimized the process of importing the circuit design into PE-Design from AutoCAD. It was discovered that when AutoCAD 'prints' a .jpg image, the image dpi is not defined in the .jpg file. To get around this problem, I defined AutoCAD's printing settings to save the image with 1 pixel corresponding to 0.1 mm, which would be equal to 254 dpi. I also defined lines as being 1 mm thick so that they would be visible. A reusable template file with the correct settings was saved for future use. After exporting the image from AutoCAD, I opened the .jpg in IrfanView—an image editing program—and manually defined the dpi as 254. After saving, the background was imported into PE-Design in 1:1 scale.

I modified the embroidery design itself by opening the previous satin stitch design, and by removing the jumps that created the 'tails.' I also extended the satin stitches underneath the solder holes to allow more contact with the components.

Notes: Background image must be saved in the same directory as the .pes file saved by PE-Design. Otherwise, the background image will not load the next time the .pes file is loaded.

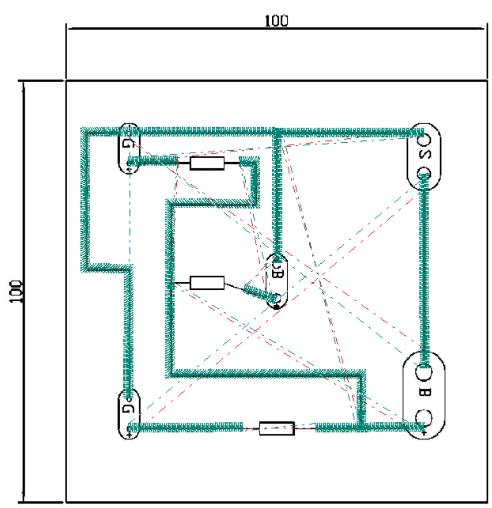

Figure 9: Digitized embroidery design.

3.3 Sewing

The circuit was sewn onto one-piece of stabilizer, which was found to be adequately stable.

The machine was loaded with Sysc20VtAg silver conductive bobbin thread and Shld2NyAg-B conductive top thread. Shld2NyAg-B was chosen as a top thread as it performs significantly better, and Sysc20VtAg was used for the bobbin as it provides dramatically less resistance.

The circuit sewed without incident, although Sysc20VtAg was found to be slightly off nominal when used for satin stitches, in that the stitches were slightly uneven and had some minor fraying; this does not appear to impact performance.

3.4 Component attachment

Components were hand sewn onto the embroidered circuit using Sysc20VtAg conductive thread. To create strong connections, the thread was looped through both the component solder holes and the satin stitches—on the inside and outside of the solder hole—four to five times. Connections must be tight so that components do not come lose. An issue was encountered with the blue LED flickering, as the connection eventually loosened, degrading performance significantly.

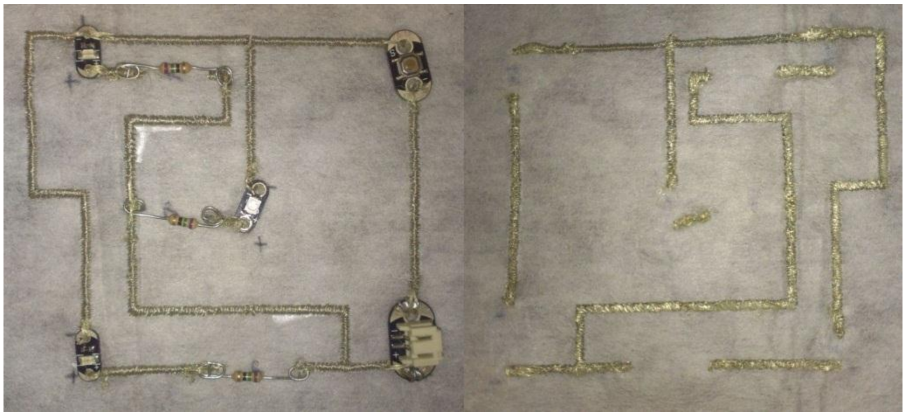

Figure 10: Front and back.

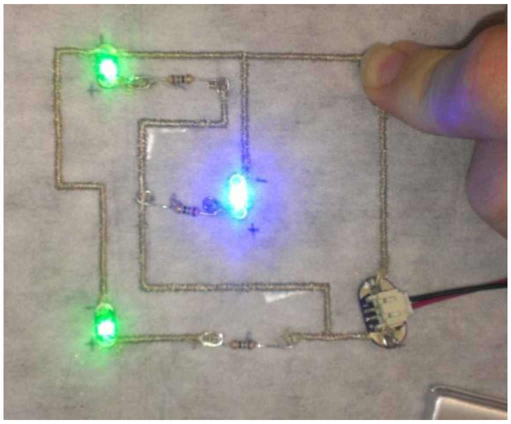

Figure 11: The e-textile with the switch activated.

3.5 Results and recommendations

I found that Shld2NyAg-B as a top thread and Sysc20VtAg as a bobbin thread is an excellent combination. Circuit integrity is excellent, and Sysc20VtAg allows resistance values as low as 0.3 ohms/inch. I also found that Sysc20VtAg works perfectly for both physically holding components in place, as well as for providing a good conductive connection. However, hand sewing is very unreliable and time consuming.

My recommendation for the next step is to test several new concepts: (a) using straight-stitches for interconnects with satin-stitch pads under solder holes to take advantage of the low resistance of Sysc20VtAg, (b) sewing components in place with the embroidery machine rather than hand-stitching, and (c) sewing with Sysc20VtAg bobbin thread and Nomex top thread, then soldering components in place.

4.0 Phase Three – Embroidering Components in Place

4.1 Overview and findings

The next e-textile created followed the same design as the previous, with a circuit that lights up three LEDs while a button is pushed. However, this time the circuit was modified to use only straight stitch interconnects to take advantage of the low resistance of Sysc20VtAg thread. The important part of this project was to test using the embroidery machine to sew components directly in place by using a template, as this would dramatically decrease manufacturing time and potentially lead to more durable connections. Overall, this method was successful; however, as suspected initially, component placement accuracy is very critical. The e-textile wasn't completed to save resources, but there was great success with the components that were sewn into place.

4.2 Embroidery design

The embroidery design was modified to use only straight stitches rather than satin stitches. I added a box, which is to be sewn first with non-conductive thread. This serves as a placement guide for a circuit overlay, which shows where to place components with high accuracy. I also added conductive 'pads' to be sewn underneath components, and triangle-shaped elements to serve as the actual connections. The triangles were formed by drawing straight-stitches back and forth between the center point of the board hole and the outside of the board. It's important to also change the sewing pitch (length of each stitch) to a very high value, and confirm that no stitches pierce the board.

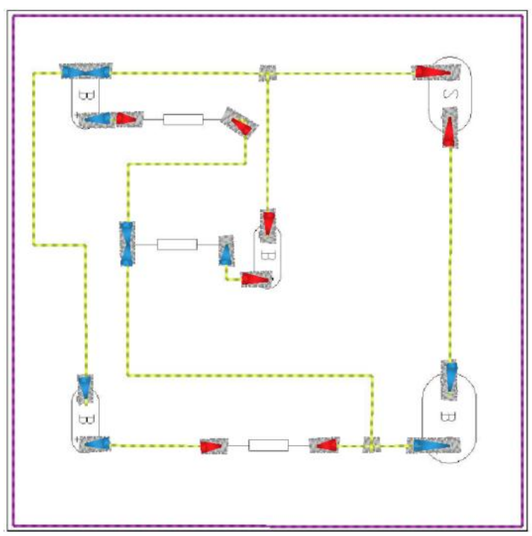

Figure 12: Digitized embroidery design.

4.3 Sewing

The circuit was sewn onto one piece of stabilizer, which was found to be adequately stable.

The first step was to sew the alignment square, using non-conductive top thread and bobbin thread. ‘Reserve Stop’ was pressed to make the machine stop after sewing the square. After this was completed, a paper cutout was overlaid onto the stabilizer precisely on top of the square. This overlay showed how to place components. The overlay was held in place using four pieces of clear tape. For the conductive circuit, the machine was loaded with Sysc20VtAg silver conductive bobbin thread and Shld2NyAg-B conductive top thread. The first step was to sew the interconnects and the conductive pads, with ‘Reserve Stop’ being used to prevent the machine from continuing after the pads were sewn. After this, machine speed was lowered to its lowest setting. Because the method is new, it was decided to stop the machine after sewing each component using ‘Reserve Stop.’ Next, the hoop was removed, the components were aligned in place and secured with clear tape, and the connections were sewn.

For the first test, actual components and conductive thread were not used—I simply used paper cutouts of components to confirm that the embroidery machine could accurately reach the holes without piercing the boards.

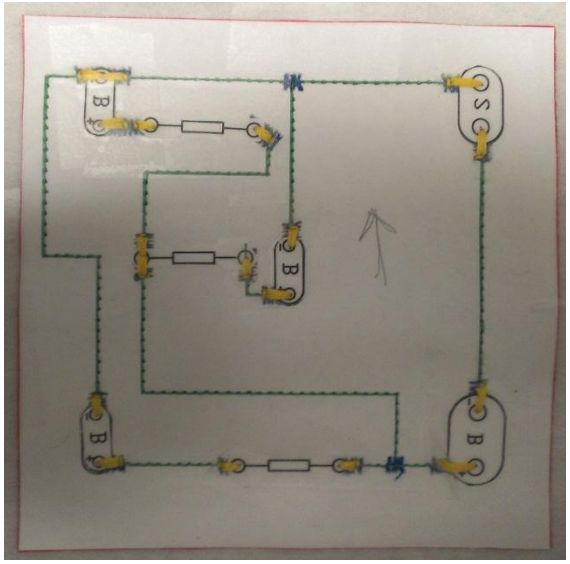

Figure 13: Sewn with paper placeholder ‘components’.

After this was found to be very successful, I decided to sew on actual components, including a blue LED and two resistors. The blue LED and first resistor sewed on with no issues. However, the second resistor was found to be partially misaligned, preventing a secure connection from being formed. This is believed to be caused by an error with how the resistor was bent into shape. To save resources, I decided not to continue with the remaining components as the method was verified to work.

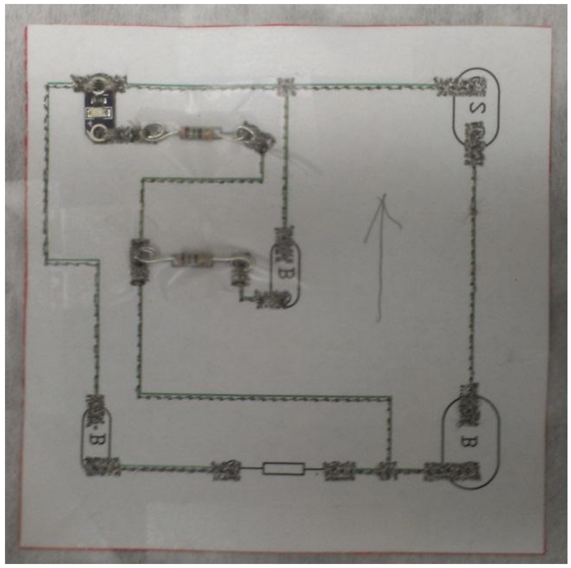

Figure 14: Sewn with real components.

4.4 Results and recommendations

Overall, this method was found to work very well. Out of the three actual components sewn into place, only one resistor was found to have an issue, which was related to how the terminals were bent into shape. It is essential to ensure that the component overlay—as well as the components themselves—are accurately placed so as to prevent a board strike or a missed hole.

My recommendation is to first try to sew a complete circuit using fewer components to verify connection integrity, and then to explore improving upon this method by printing the component overlay onto tear away stabilizer, as well as to find a better way to shape resistor’s terminals such that they can be accurately placed.

5.0 Phase Four – Embroidering in Place with Strain Relief

5.1 Overview and findings

The next e-textile follows a more simple design, with an LED board and a board containing an integrated switch, battery connection, and resistor. This project was to both continue testing using the machine to sew in place, as well as to test a method of strain relief using a three-dimensional (3D) printed brace. Overall, the project was successful. Both the components and the braces sewed on without any issues. It was found that on the first e-textile created, the LED board was faulty; however, testing revealed that the connections themselves were satisfactory. A second e-textile was created without incident. On initial inspection, the braces seem to do a satisfactory job of relieving strain from the board connections. However, more detailed analysis on their effectiveness may be required.

5.2 Brace design

The strain relief braces are designed to slip around the circuit boards after the board is sewn in place. Next, the brace is to be sewn in place from all corners. The concept is that when the e-textile is bent, the strain would be moved from the connection point of the board, to the less critical connection point of the brace. The brace can also be sewn with stronger non-conductive threads.

The brace was designed in Pro/Engineer as a solid model. Pro/Engineer was chosen as it is the standard mechanical CAD tool used at NASA Johnson Space Center. From Pro/Engineer, the model was exported as a .stl file, which was then 3D printed by a MakerBot Replicator 2X using ABS plastic.

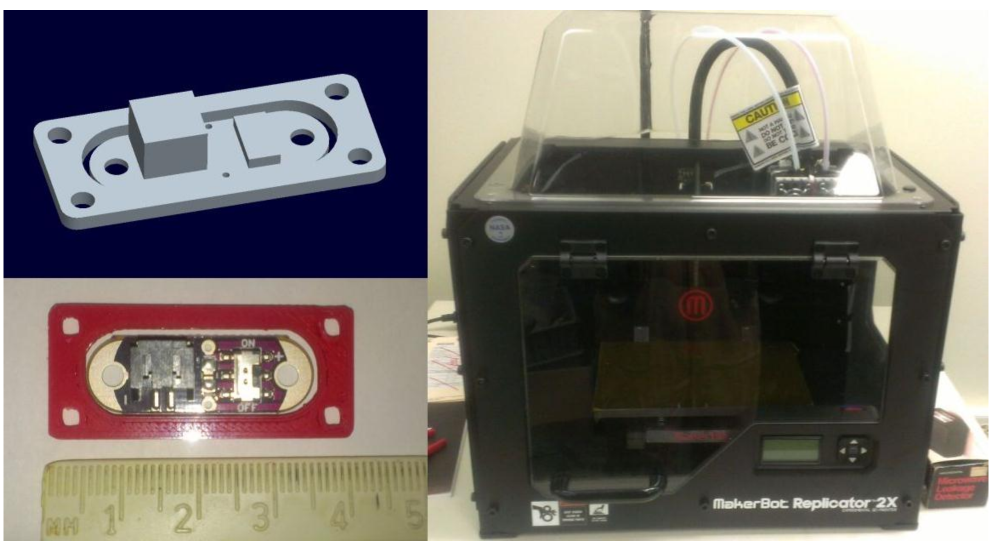

Figure 15: Top left: Solid model of a brace and board. Bottom left: 3D printed brace. Right: MakerBot Replicator 2X 3D Printer.

5.3 Circuit layout

The circuit layout was designed in AutoCAD using the previous project's circuit design as a template. To improve the process of designing layouts, 'top views' of the braces and the boards were generated in Pro/Engineer and converted to AutoCAD's .dwg drawing format. These drawings could then be inserted into a circuit layout drawing in AutoCAD, where they can be freely repositioned.

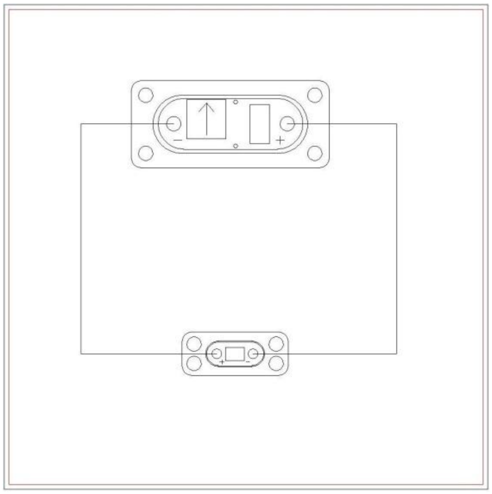

Figure 16: Circuit layout.

5.4 Embroidery design

The embroidery design is made up of several layers (represented by different thread colors): the alignment square, the conductive inter connects, the conductive component attachments, and the brace attachments. A few changes were made in the process of creating the embroidery design. Once again, straight-stitch interconnects were used. However, this time, conductive pads were not sewn under components as it was believed the conductive pads were unnecessary.

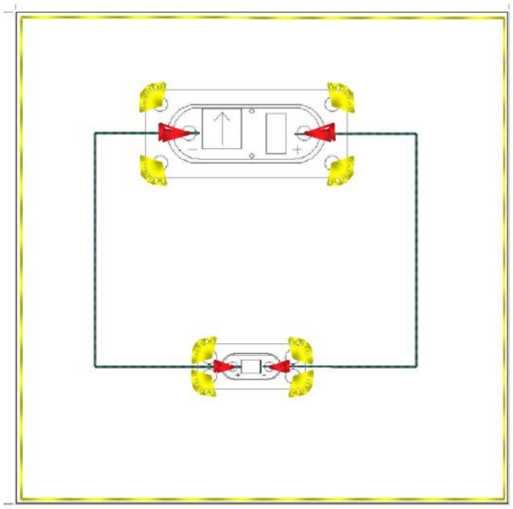

Figure 17: Digitized embroidery design.

5.5 Sewing

The circuit was sewn using the previous method of having an overlay template. However, because using the machine to sew components was successful, it was decided to secure all components without stopping the machine. Once again, Sysc20VtAg silver conductive bobbin thread and Shld2NyAg-B conductive top thread were used. After the components were sewn into place, the braces were aligned and sewn using non-conductive top and bobbin thread. After the e-textile was completed, loose conductive thread was tripped from the bottom to avoid shorts.

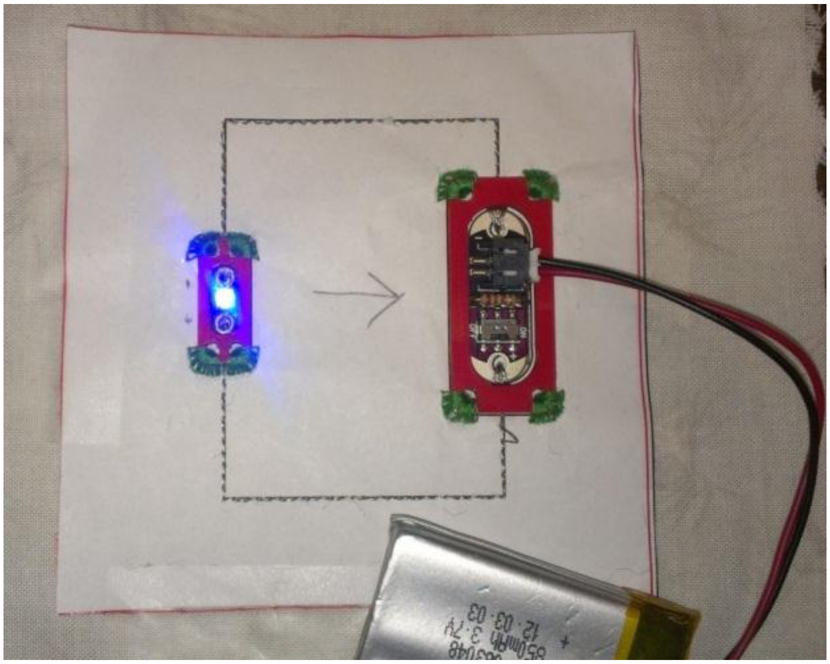

Figure 18: Completed e-textile. The circuit overlay has yet to be removed.

5.6 Results and recommendations

This method was found to work well. The LED board was secured tightly in place; however, the battery and switch board was found to be somewhat loose. If the board is manipulated by pushing downward, sometimes the connection can be lost, causing the LED to flicker. This could perhaps be fixed by either reintroducing the conductive pads, by making the stitching tighter, by making the tension tighter, and/or by soldering. On initial inspection, the strain relief braces appear to do an adequate job of relieving strain from the component attachments. However, their effectiveness may need closer evaluation.

My recommendation is to explore printing the circuit layout onto tear away stabilizer instead of paper, as well as to explore the possibility of insulating and waterproofing sewn traces with non-conductive satin stitches, and/or by applying Room Temperature Vulcanizing (RTV) or another substance. To improve component attachment reliability, if Sysc20VtAg or another high-temperature conductive thread can be made to work as a top thread, it may even be possible to solder connections using a solder reflow machine.

6.0 Conclusion

Many lessons were learned about e-textile manufacturing throughout the four project iterations. It was found that using Sysc20VtAg—a harder to work with, but more conductive thread—works well in the bobbin of the embroidery machine, and that Shld2NyAg-B—an easier to work with but less conductive thread—works well as a top thread. Embroidering components in place using an overlay was found to be the fastest and most reliable way of manufacturing e-textiles, with a big improvement over previous methods. Lastly, on initial observation, 3D strain relief braces appear to work well for solving issues with strain on component connections.

There were a few recommendations that could not be explored due to time constrains. These include printing circuit overlays on tear away stabilizer to ease the manufacturing process; exploring the use of more difficult threads in the embroidery machine by adjusting tension settings and using silicon spray as a lubricant; methods of insulating circuits by using non-conductive satin stitches, RTV or other coatings, and plastic layers; and soldering using a solder reflow machine by embroidering circuits on a flame-retardant textile such as Nomex with high-temperature thread.

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12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Wearable Electronic-textile Application & Research (WEAR) Lab's primary focus is on developing electronic-textiles (e-textiles) and wearable technologies. An e-textile combines traditional textiles, such as fabric and thread, with electronics elements, such as microcontrollers, sensors, light-emitting diodes, displays, and tactors. Previously, the WEAR lab developed e-textiles by either sewing or embroidering conductive interconnects using conductive silver thread. Next, components would be either hand sewn or soldered in place. However, there have been difficulties in working with conductive threads as they are prone to fraying, breaking, and curling, especially when used in an embroidery machine. Further, hand sewing components in place is tedious and has led to component connections that would break down over time from strain. The WEAR lab recently acquired a Brother PR-650e embroidery machine, which allows for both larger e-textiles to be manufactured, as well as for greater control over thread tension. In developing procedures for using the Brother PR-650e to manufacture e-textiles, work was broken into individual phases. As lessons were learned from each phase, recommendations were made on what to adjust for the next phase.

14. SUBJECT TERMS	15. NUMBER OF PAGES	16. PRICE CODE
textiles; circuits; sewing; clothing; sensors; light-omitting diodes; computer aided manufacturing	24	

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
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